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The Physics of Ion Decoupling in Magnetized Plasma Explosions

D. Hewett, D. Larson, S. Brecht

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The Physics of Ion Decoupling in Magnetized Plasma Explosions

WCI WEAPONS AND COMPLEX INTEGRATION

Dennis W. Hewett, David J. Larson, Stephen H. Brecht

LLNL HANE Project

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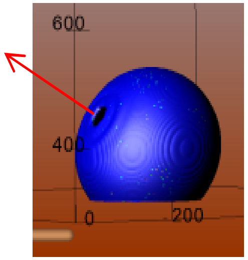
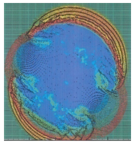
Overview: Decoupled Ions in HANES

When a finite pulse of plasma expands into a magnetized background plasma, MHD predicts the pulse expel background plasma and its B-field—i.e. cause a magnetic "bubble".



The expanding plasma is confined within the bubble, later to escape down the B-field lines. MHD suggests that the debris energy goes to expelling the B-field from the bubble volume and kinetic energy of the displaced background.



For HANEs, this is far from the complete story.

For many realistic HANE regimes, the long mean-free-path for collisions necessitates a Kinetic Ion Simulation Model (KISM). The most obvious effect is that the debris plasma can decouple and slip through the background plasma.

The implications are:
1) the magnetic bubble is not as large as expected and
2) the debris is no longer confined within the magnetic bubble.

Traditional MHD Modeling of HANES Misses Important Physics

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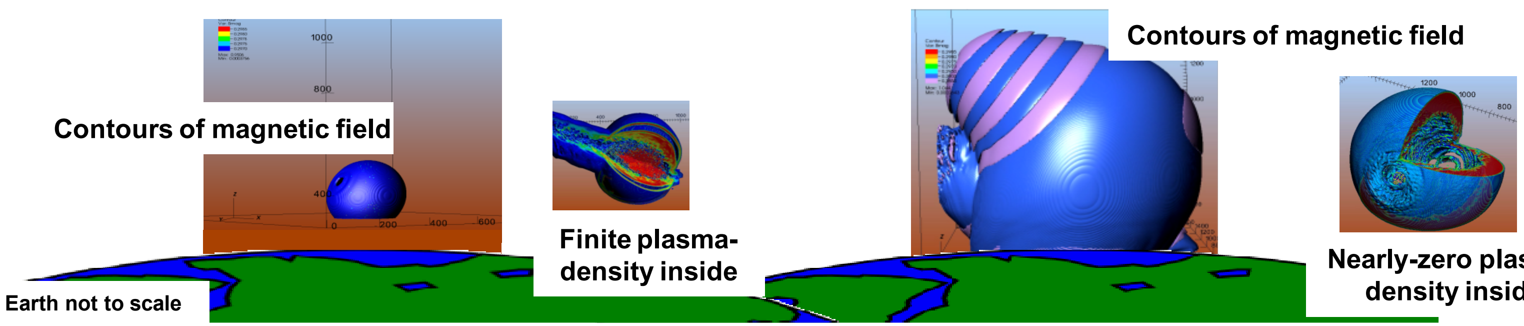
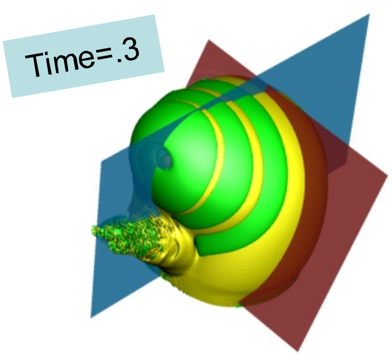
Consider a HANE-relevant debris pulse into the ambient ionospheric density at 400 km altitude. For typical densities (here 3e5 O^{+1} ions/cm^3), a STARFISH relevant explosion produces magnetic bubbles such as these

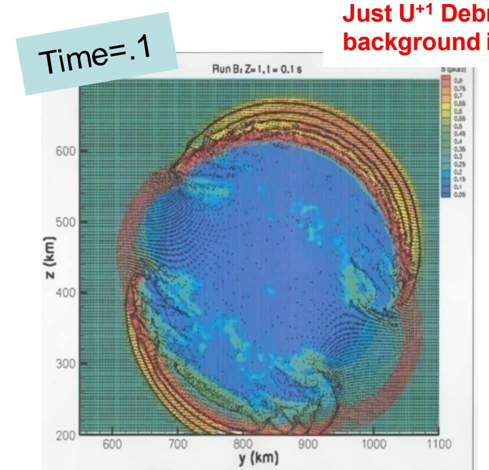




ambient densities, charge state +1

Today we focus on the early-time coupling of debris ions to the background plasma

Just U^{+1} Debris & O^{+1} background ionosphere



Brecht, S. H., D. W. Hewett, and D. J. Larson (2009), "A magnetized, spherical plasma expansion in an inhomogeneous plasma: Transition from super- to sub-Alfvénic", Geophys. Res. Lett., 36, L15105, doi:10.1029/2009GL038393, 6 August 2009

Introducing More Realism reveals important non-MHD behavior

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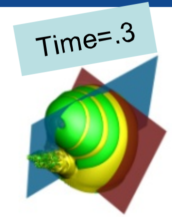
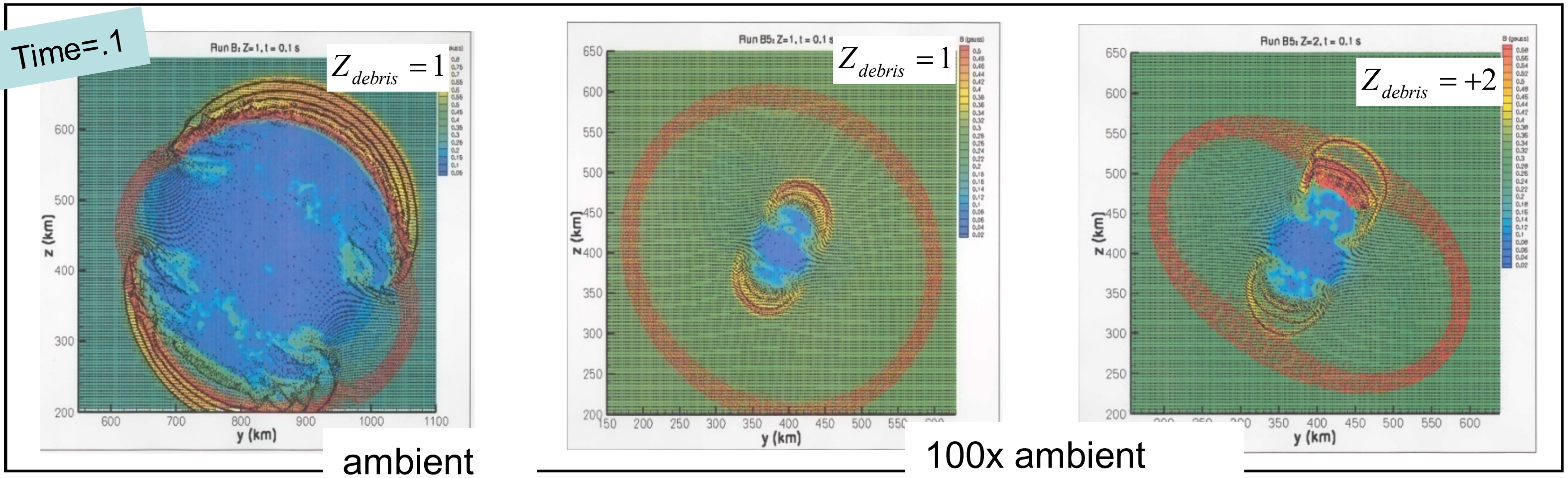


Parameter changes towards more realistic physics lead to interesting changes in coupling of the debris to the ionosphere.



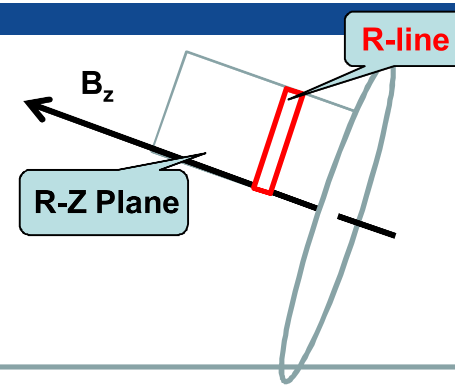
Traditional modeling

Flash ionization

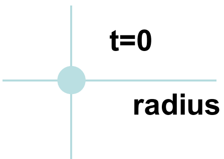
More realistic debris charge state

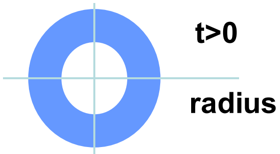
Ion debris decoupling is very sensitive to the charge states and drives a requirement for improved atomic physics

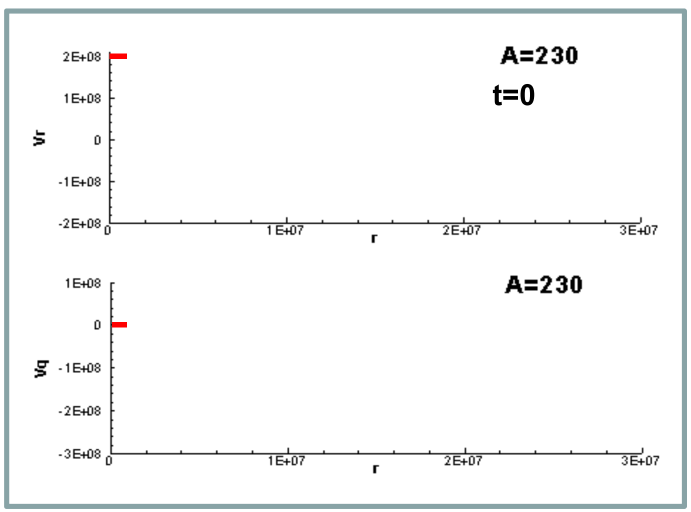
This Physics is easier to see in 1-D

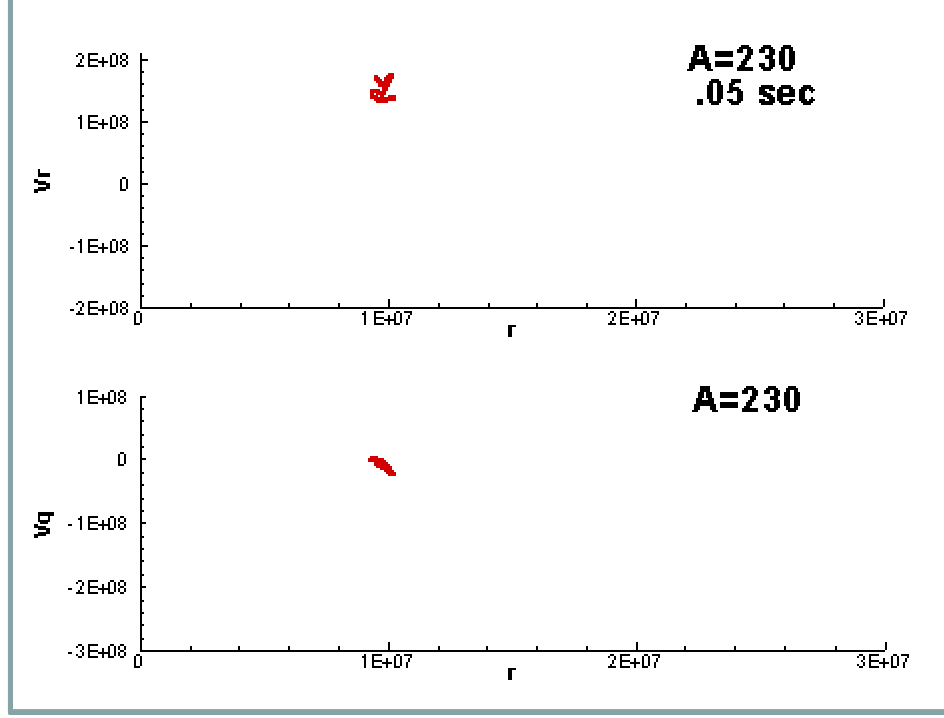


Initial debris configuration:
v_r=2e8 cm/sec v_θ=0.
homogeneous , 20 km radius debris "puff"









Here is the same physics with added background for a typical coupled & decoupled case

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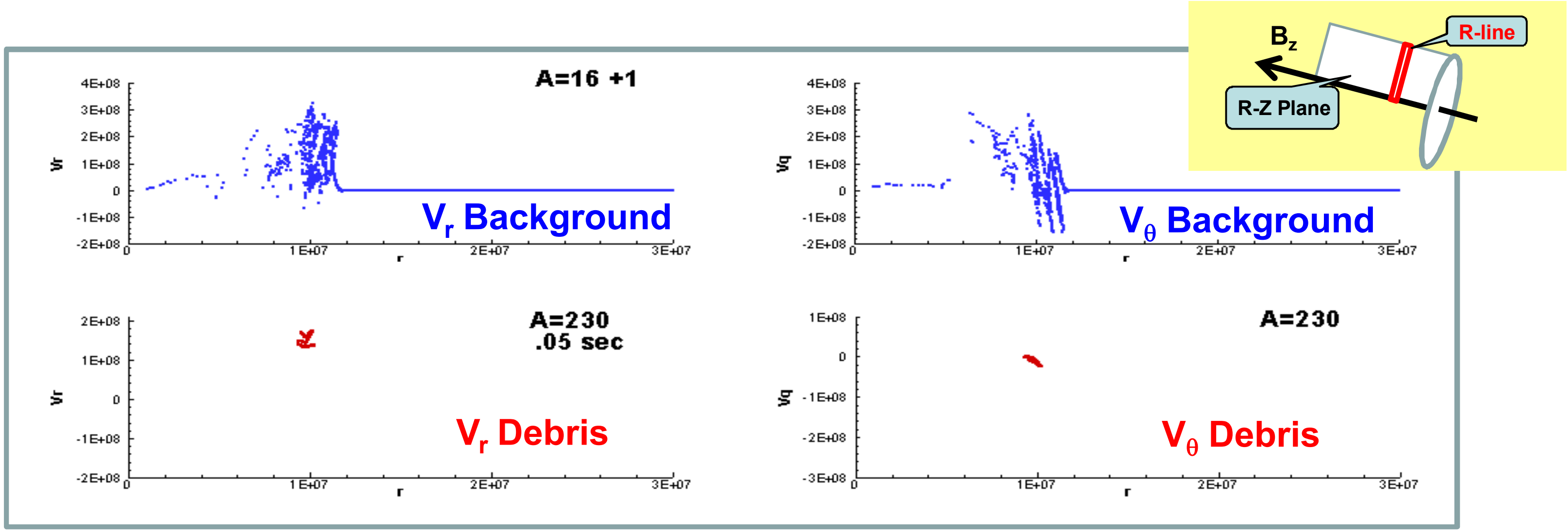
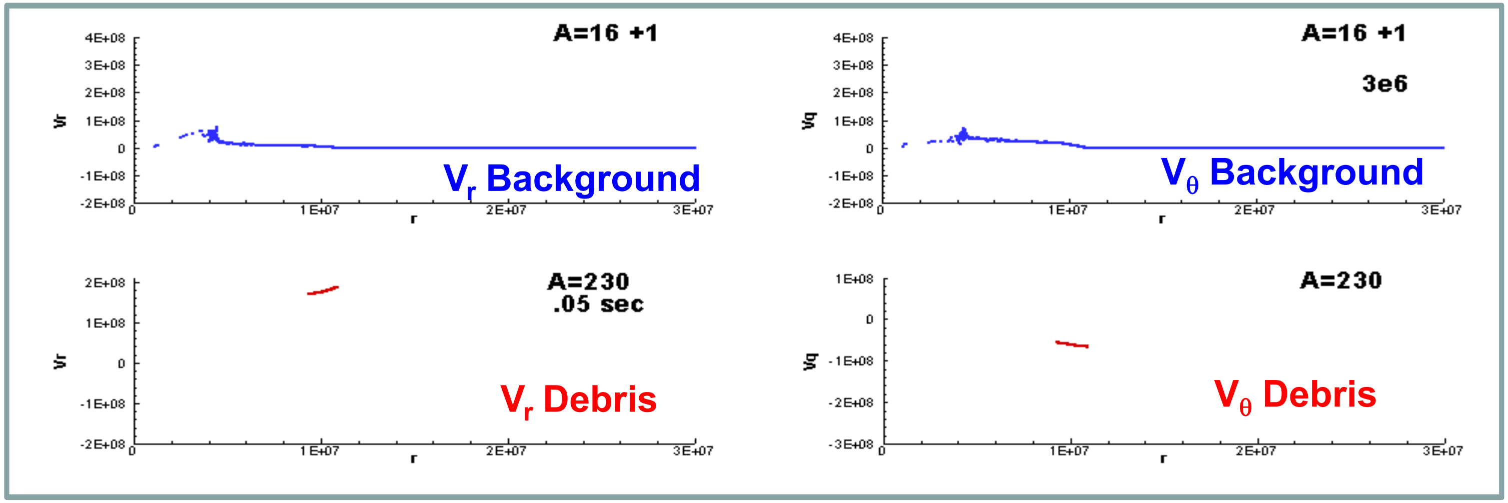
Coupled



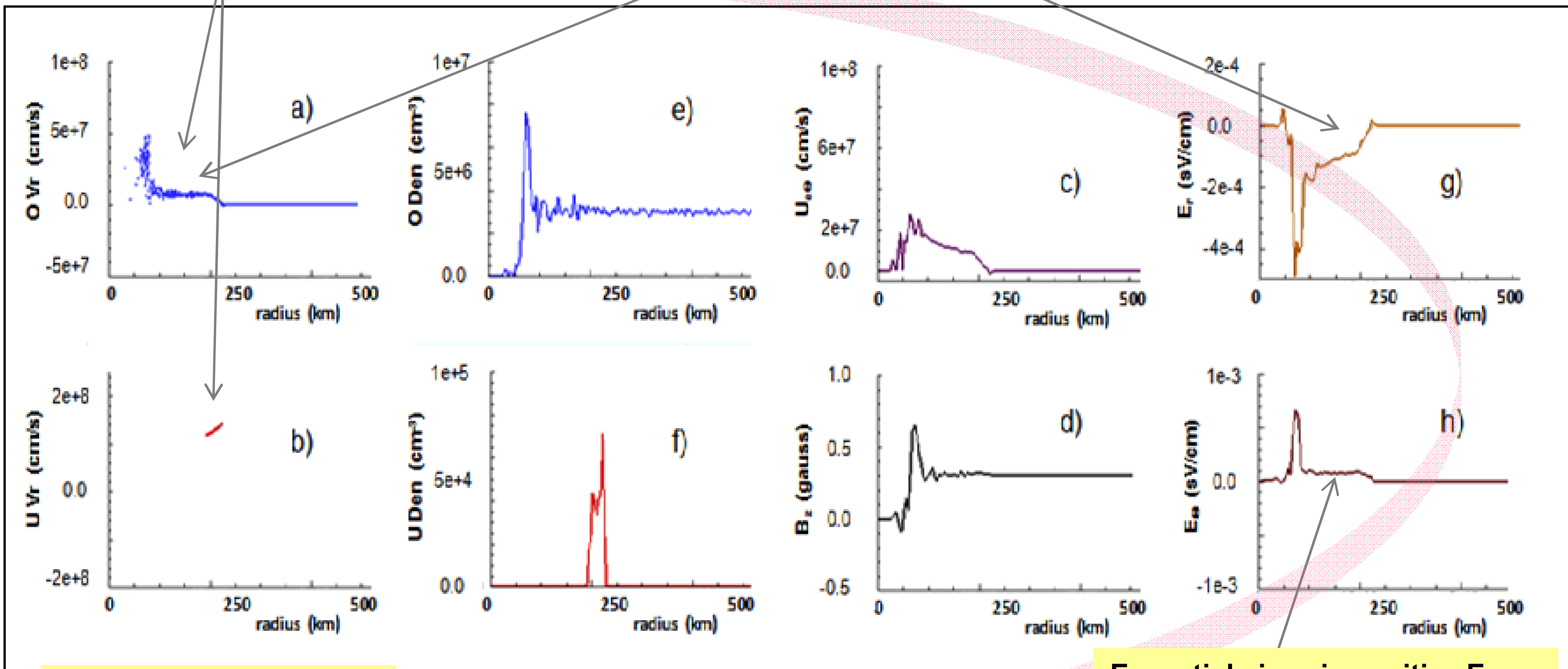
Decoupled



A run with U slipping through O reveals what's important for decoupling

U^{+1} slips through

U^{+1} moves out in spite of negative E_r



And the criterion for decoupling is…

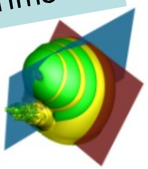
$$\left(\frac{\pi}{2}-1\right)\frac{Z_D n_D}{Z_B n_B}<1$$

It is just this E_Θ that gives the ExB drift at the Alfvén speed.

Essential piece is positive E_Θ due to debris outflow in quasi-neutral equations

We developed a simple criterion for when Kinetic Ion Models are essential for modeling HANE

Time=.3

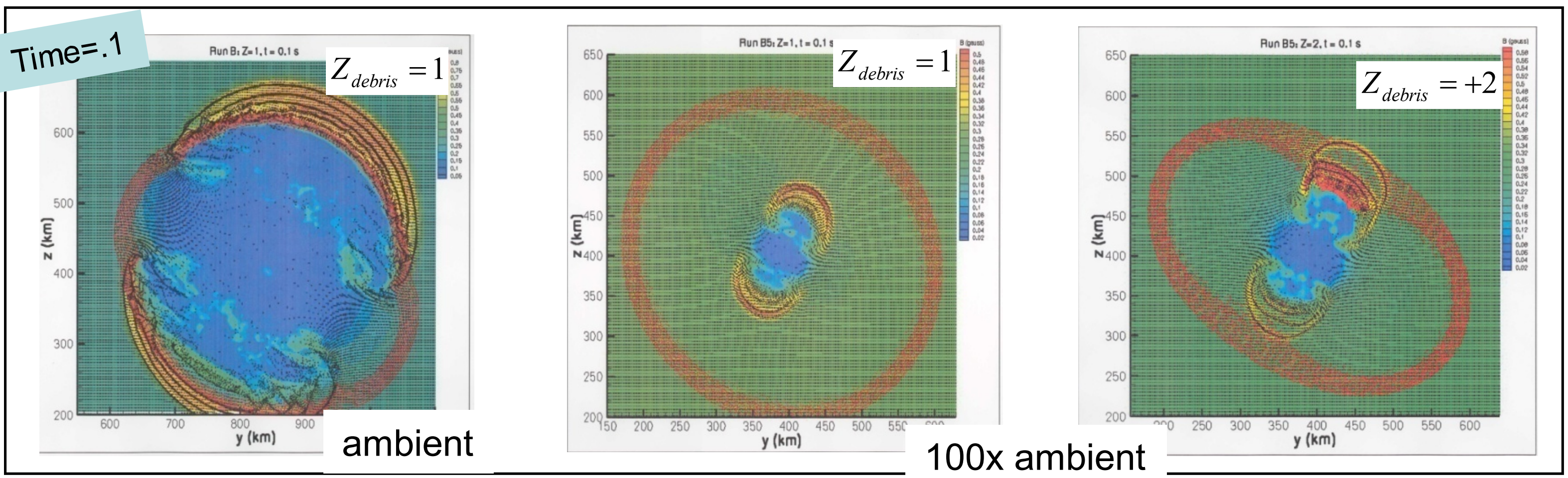


Debris "decouples" depending on background electron density

$$Z_B n_B = \left(\frac{\pi}{2} - 1\right) Z_D n_D$$

Higher debris charge states couple more strongly

Just U[+1] Debris & O[+1] background ionosphere



Traditional modeling

Flash ionization

More realistic debris charge state

Ion debris decoupling is very sensitive to the charge states and drives a requirement for improved atomic physics

Consider the fields generated by the debris in this quasi-neutral, collisionless plasma

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Start with the electron momentum equation

$$m_e n_e D_t \vec{u}_e = e n_e \vec{E} + \nabla P_e + \vec{J}_e \times \vec{B}/c$$

In the zero electron mass limit, we solve for E

$$\vec{E} = \frac{\nabla P_e}{e n_e} - \frac{\vec{J}_e \times \vec{B}}{e n_e c}$$

Assuming quasi-neutrality and using the Darwin limit of Ampere's law,

$$n_e = \sum_{species} Z_s n_s \qquad c\nabla \times \vec{B} = 4\pi\left(\vec{J}_i + \vec{J}_e\right)$$

the expression for E becomes

$$\vec{E} = \frac{\nabla P_e}{e n_e} - \frac{\vec{J}_e \times \vec{B}}{e n_e c} \qquad \vec{J}_e = \frac{c}{4\pi}\nabla \times \vec{B} - \sum_{species} \vec{J}_s \quad \Rightarrow \quad \vec{E} = \frac{\nabla P_e}{e \sum_{species} Z_s n_s} - \frac{\left(\frac{c}{4\pi}\nabla \times \vec{B} - \sum_{species} \vec{J}_s\right) \times \vec{B}}{ec \sum_{species} Z_s n_s}$$

For this simple 1-D case, early in time

$$\nabla P_e \sim 0 \ \ \& \ \ \nabla \times \vec{B} \sim 0 \quad \longrightarrow \quad \boxed{\vec{E} = \frac{\left(\vec{J}_{Di} + \vec{J}_{Bi}\right) \times \vec{B}}{e n_e c}}$$

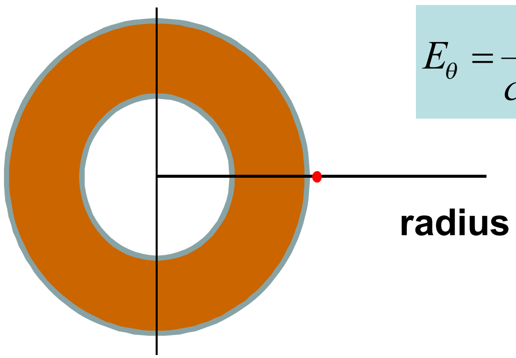
Linearize:
$u_{D\theta} \sim 0 \quad u_{Br} \sim 0$

so what matters is

$$E_\theta = \frac{Z_D n_D u_{Dr}}{c\left(Z_D n_D + Z_B n_B\right)} B_z \qquad E_r = -\frac{Z_B n_B u_{B\theta}}{c\left(Z_D n_D + Z_B n_B\right)} B_z$$

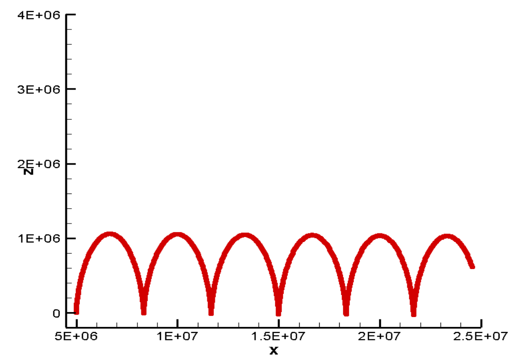
The debris generates electric fields as it passes through the background, however not in the "obvious" directions.

Consider how a background ion responds to these fields as the debris passes



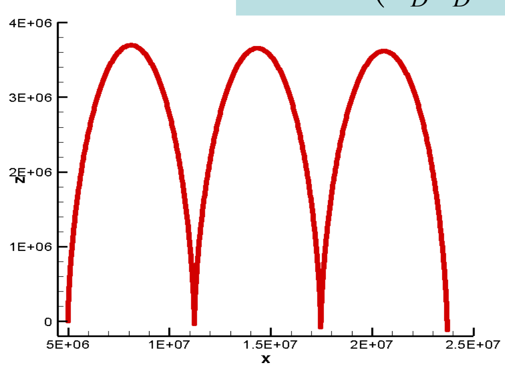
$$E_\theta = \frac{Z_D n_D u_{Dr}}{c\left(Z_D n_D + Z_B n_B\right)} B_z$$

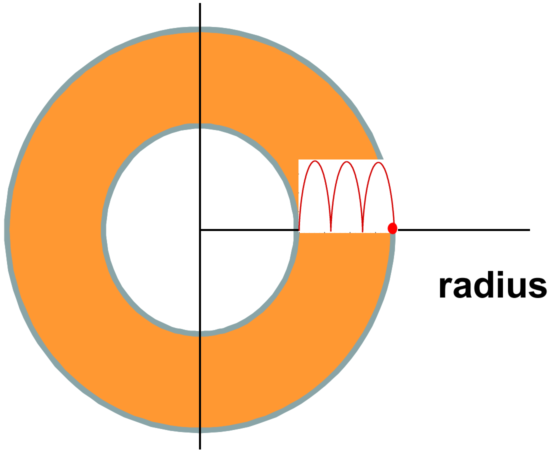
With just the azimuthal field



plus

$$E_r = -\frac{Z_B n_B u_{B\theta}}{c\left(Z_D n_D + Z_B n_B\right)} B_z$$





The background will be left behind if it acquires too little "speed"

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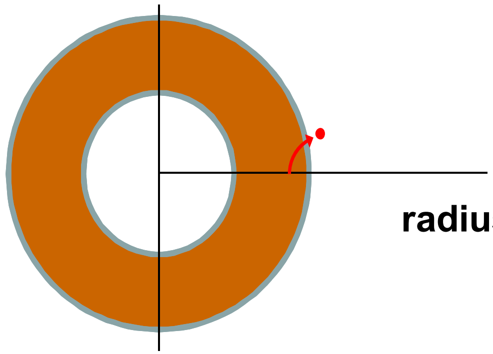
To coupling, the background ions must acquire enough velocity to remain in front of the debris

The secret of the decoupling lies in the

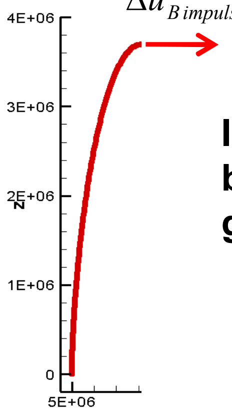
1) magnitude of E_θ

2) time it spends in this field

$$E_\theta = \frac{Z_D n_D u_{Dr}}{c\left(Z_D n_D + Z_B n_B\right)} B_z$$



$\Delta u_{B\,impulse\,\theta}$



In this simple case, this speed must be acquired in roughly the first ¼ of a gyro-period. Combining...

$$\frac{\Delta u_{B\,impulse\,\theta}}{\Delta t} = \frac{Z_B e}{m_B} E_\theta \qquad \Delta t = \frac{\pi}{2\,\omega_{cB}}$$

$$\Delta u_{B\,impulse\,\theta} = \frac{\pi}{2}\frac{cE_\theta}{B_z} = \frac{\pi}{2}\frac{c}{B_z}\frac{Z_D n_D u_{Dr}}{c\left(Z_D n_D + Z_B n_B\right)} B_z$$

$$= \frac{\pi}{2}\frac{Z_D n_D u_{Dr}}{\left(Z_D n_D + Z_B n_B\right)} = \frac{\pi}{2}\frac{Z_D n_D}{\left(Z_D n_D + Z_B n_B\right)} u_{Dr}$$

$$\frac{\Delta u_{B\,impulse\,\theta}}{u_{Dr}} = \frac{\pi}{2}\frac{Z_D n_D}{\left(Z_D n_D + Z_B n_B\right)}$$

so the debris is *DE*coupled if

$$\frac{\Delta u_{B\,impulse\,\theta}}{u_{Dr}} = \left(\frac{\pi}{2} - 1\right)\frac{Z_D n_D}{Z_B n_B} \equiv \alpha_{dc} < 1$$

Another way to look at this...

Remember the $u_{B\theta}$ assumption

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Look at the ratio $\dfrac{E_r}{E_\theta}$

$$E_r = -\frac{Z_B n_B u_{B\theta}}{c\left(Z_D n_D + Z_B n_B\right)} B_z \qquad E_\theta = \frac{Z_D n_D u_{Dr}}{c\left(Z_D n_D + Z_B n_B\right)} B_z$$

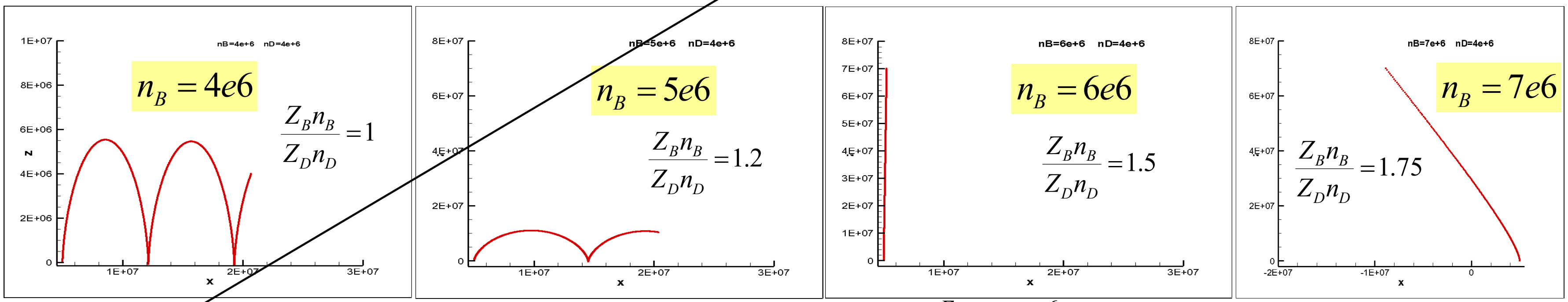
$$\frac{\Delta u_{Bimpulse\theta}}{u_{Dr}} = \frac{\pi}{2} \frac{Z_D n_D}{\left(Z_D n_D + Z_B n_B\right)}$$

$$\frac{E_r}{E_\theta} = \frac{-\dfrac{Z_B n_B u_{B\theta}}{c\left(Z_D n_D + Z_B n_B\right)} B_z}{\dfrac{Z_D n_D u_{Dr}}{c\left(Z_D n_D + Z_B n_B\right)} B_z} = -\frac{Z_B n_B u_{B\theta}}{Z_D n_D u_{Dr}}$$

$$\frac{E_r}{E_\theta} = -\frac{Z_B n_B}{Z_D n_D} \frac{\pi}{2} \frac{Z_D n_D}{\left(Z_D n_D + Z_B n_B\right)} = -\frac{\pi}{2} \frac{Z_B n_B}{\left(Z_D n_D + Z_B n_B\right)}$$

$$\frac{E_r}{E_\theta} = -\frac{\pi}{2} \frac{Z_B n_B}{\left(Z_D n_D + Z_B n_B\right)}$$

A series of runs with increasing n_B shows



$$\frac{E_r}{E_\theta} = -\frac{\pi}{2}\frac{4}{(4+4)} = -\frac{\pi}{4} \qquad \frac{E_r}{E_\theta} = -\frac{\pi}{2}\frac{5}{(4+5)} = -.5555\ldots\frac{\pi}{2} \qquad \frac{E_r}{E_\theta} = -\frac{\pi}{2}\frac{6}{(4+6)} = -.6\frac{\pi}{2} \qquad \frac{E_r}{E_\theta} = -\frac{\pi}{2}\frac{7}{(4+7)} = -.636\ldots\frac{\pi}{2}$$

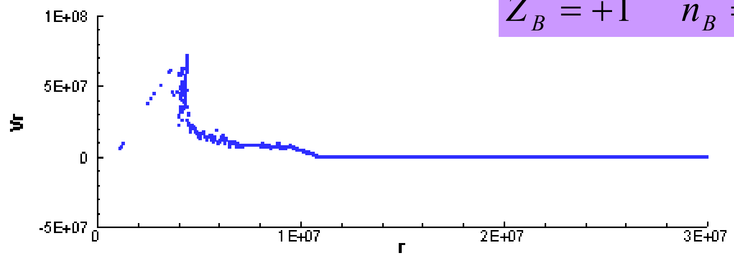
Coupled **Decoupled**

Note that $\dfrac{E_r}{E_\theta} = 1$ **at** $\dfrac{Z_B n_B}{Z_D n_D} = 1.7519\ldots$**.**

$Z_B n_B > \left(\frac{\pi}{2} - 1\right) Z_D n_D$ is not quite the whole story

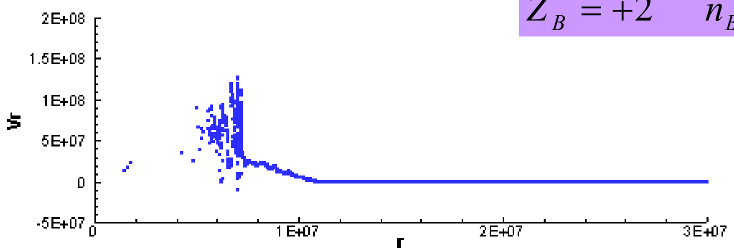
Simple formula would suggest that the product $Z_B n_B$ is all that matters...
However...

$Z_B = +1 \quad n_B = 3e6$

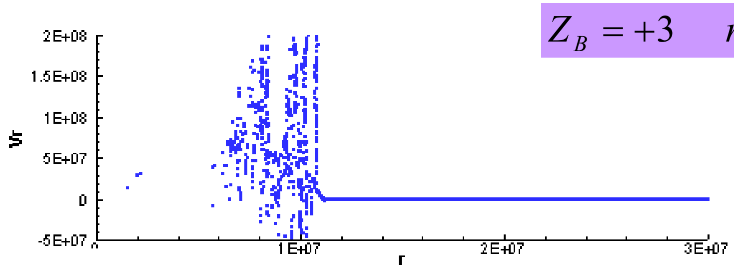


Decoupled

$Z_B = +2 \quad n_B = 1.5e6$



$Z_B = +3 \quad n_B = 1e6$



Coupled

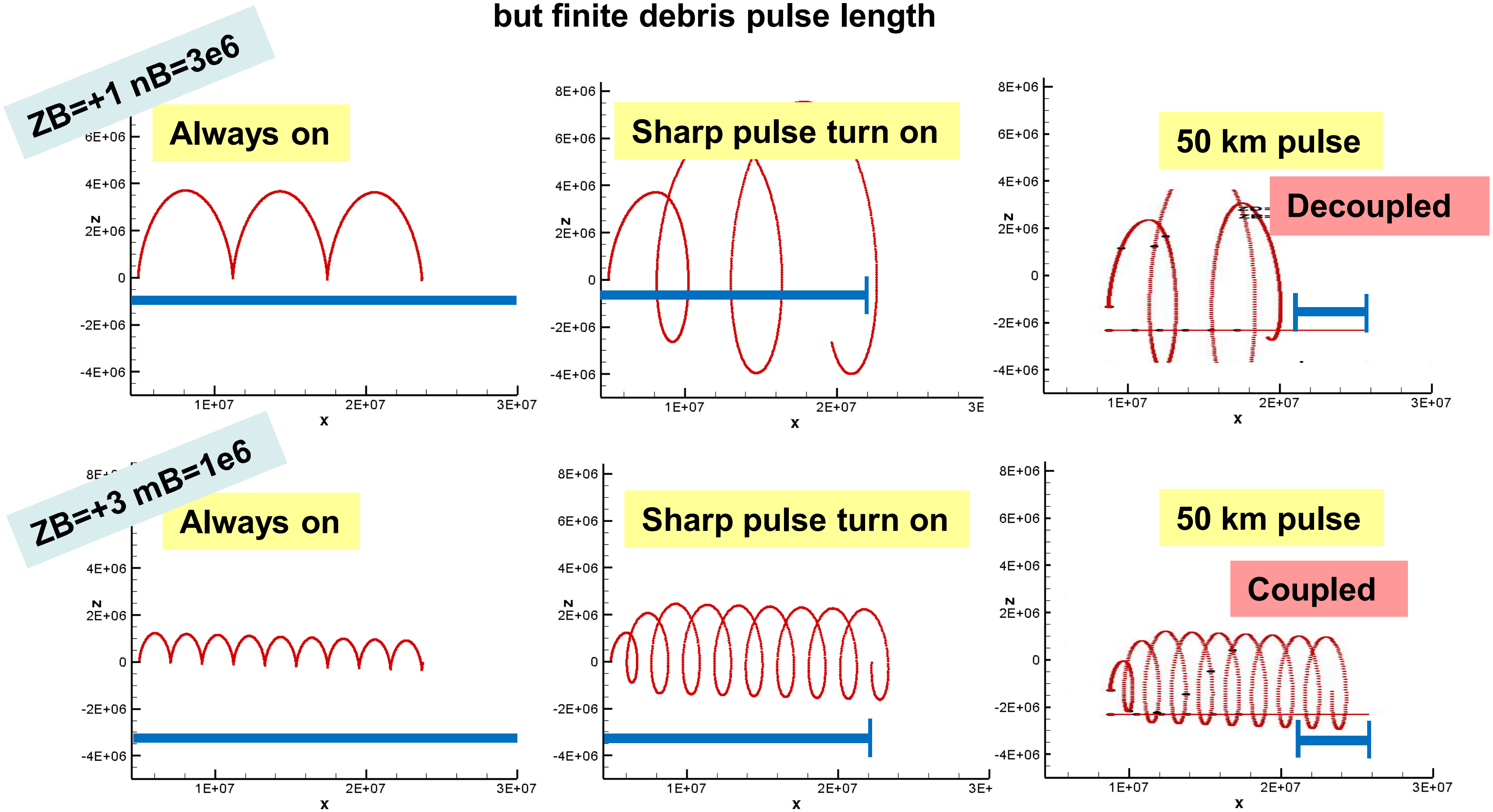
Higher charge state Z_B (smaller gyro-radius), enhances debris coupling

ZD=+1 nD=4e6

Use these fields

$$E_r = -\frac{Z_B n_B u_{B\theta}}{c(Z_D n_D + Z_B n_B)} B_z \qquad E_\theta = \frac{Z_D n_D u_{Dr}}{c(Z_D n_D + Z_B n_B)} B_z$$

but finite debris pulse length



Enhanced coupling leads to another threshold that plays in debris coupling

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In addition to the electron density threshold $\boxed{Z_B n_B > \left(\frac{\pi}{2} - 1\right) Z_D n_D}$,

DEcoupling requires the gyro-radius to be BIGGER than the pulse length or

$$r_{B\,larmor} > \delta_{pulse}$$

$$r_{B\,larmor} = \frac{\Delta u_{B\,impulse\,\theta}}{\omega_{Bc}} \qquad \omega_{Bc} = \frac{Z_B e B_z}{c m_B}$$

$$r_{B\,larmor} = \frac{c m_B}{2eB_z} \frac{Z_D n_D u_{Dr}}{\left(Z_D n_D + Z_B n_B\right)} \frac{1}{Z_B} > \delta_{pulse}$$

$$\frac{Z_D n_D}{\left(Z_D n_D + Z_B n_B\right)} > \omega_B \frac{\delta_{pulse}}{u_{Dr}}$$

$$\boxed{r_{B\,larmor} = \frac{Z_D n_D u_{Dr}}{\left(Z_D n_D + Z_B n_B\right)} \frac{c m_B}{2eB_z} \frac{1}{Z_B} > \delta_{pulse}}$$

that shows the observed additional dependence on background charge state.

Summary: Ion Decoupling in Magnetized Plasma Explosions

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Super Alfvénic debris HANE expansions into ionosphere have been shown computationally to decouple from the ionosphere.

Simple, linear arguments have been developed that suggest threshold conditions required for decoupling (or non-fluid-like behavior) to occur.

$$\frac{\pi}{2}\frac{Z_D n_D}{\left(Z_D n_D + Z_B n_B\right)} < 1$$

$$\frac{c m_B}{2 e B_z}\frac{Z_D n_D u_{Dr}}{\left(Z_D n_D + Z_B n_B\right)} > Z_B \delta_{pulse}$$

This decoupling has interesting implications for both EMP and belt pumping.

Reconsideration of the STARFISH event suggest that these threshold conditions are relevant, and strongly dependent on the initial parameters of the HANE event.

Take away concepts:

Even in linear analysis, finite gyro-radii effect matter.

Threshold seem to apply species by species

(the species in question is the “debris”, all others are part of the “background”)

MHD/Fluid codes will not see these effects